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# Microwave Beam Power Transmission at an Arbitrary Range

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## ABSTRACT

The power transfer efficiency between two circular apertures at an arbitrary range is obtained numerically. Two apertures can have generally different sizes and arbitrary taper illuminations. The effect of distance and taper illumination on the transmission efficiency are investigated for equal size apertures. The result shows that microwave beam power is more effective at close ranges, namely distances less than  $2D^2/\lambda$ . Also shown was the power transfer efficiency increase with taper illumination for close range distances. A computer program was developed for calculating the power transfer efficiency at an arbitrary range.

## INTRODUCTION

The problem of microwave beam power transmission between two aperture antennas have been studied extensively (for example refs. 1-5) in open literature. The purpose of this paper is to determine the effective range for reliable and efficient beam power transfer between two aperture antennas. The transmitting tangential aperture field is simulated with a tapered aperture field distribution. A numerical evaluation of Kirchhoff and Helmholtz vector diffraction (ref. 6) solution is used to calculate the electric and magnetic fields distribution at arbitrary observation distances. To obtain the transmission efficiency the power transmitted is compared to the power intercepted by receiving aperture antenna located at an arbitrary distance from the transmitting antenna (see Figure 1). A description and a copy of the program are included in appendixes A and B, respectively.

## POWER TRANSFER EFFICIENCY

Let antennas  $A_1$  and  $A_2$  have generally dissimilar circular apertures of radii  $a_1$  and  $a_2$ , respectively, as shown in Figure 1. The antennas are separated by a length  $d$  along a common centerline ( $z$ -axis). This axis is perpendicular to the aperture planes of  $A_1$  and  $A_2$ . The antennas are assumed to be matched to their feeding lines. Let assume that the transmitting antenna radiates an amount of power  $P_t$  and the receiving antenna intercepts an amount of power  $P_r$ . The transmission efficiency is given as:

$$\eta = P_r / P_t \quad (1)$$

The transmitted power  $P_t$  can be expressed as:

$$P_t = .5 \iint \text{RE} (E_t(x,y,0) \times H_t^*(x,y,0)) \hat{e}_z \, dS \quad (2)$$

and the received power  $P_r$  can be expressed as:

$$P_r = .5 \iint \text{RE} (E_r(x,y,d) \times H_r^*(x,y,d)) \hat{e}_z \, dS \quad (3)$$

where the asterisk indicates the complex conjugate values,  $\hat{e}_z$  is the unit vector in the  $z$  direction,  $E_t(x,y,d)$  is the tangential electric field component, and  $H_t(x,y,d)$  is the tangential magnetic component of the field at an arbitrary location. The components  $H_t(x,y,0)$ ,  $E_r(x,y,d)$ , and  $H_r(x,y,d)$  can be expressed in terms of  $E_t(x,y,0)$  which uniquely determines the field in the entire half-space  $z > 0$  (ref. 7). The electric and magnetic fields at  $z = 0$  are assumed to have the following forms respectively:

$$E_t(x,y,0) = E_0(C + (1 - C)(1 - (p / R)^2))^p \times \quad (4)$$

$$H_t(x,y,0) = (\hat{e}_z \times E_t(x,y,0)) / Z_0 \quad (5)$$

where the parameter  $C$ ,  $p$ ,  $R$  are defined as:

$$C = 10^{-ET/20} \quad , \quad ET: \text{edge taper in dB} \quad (6)$$

$$p = x^2 + y^2 \quad , \quad \text{radius} \quad (7)$$

$$R \quad , \quad \text{radius of aperture } A_1 \quad (8)$$

The  $E_r$  and  $H_r$  fields due to the above aperture distribution are given by:

$$E_r(x,y,d) = \iint E_t(x,y,0) e^{-jk_r} ((1/r)(jK + 1/r) n \cdot r) dS \quad (9)$$

$$H_r(x,y,d) = (e_z \times E_r(x,y,d)) / Z_0 \quad (10)$$

Figure 2 depicts all required parameters to evaluate equations (9) and (10). Since the observation points are in the near field of the aperture, equations (9) and (10) are general, do not simplify further. In order to compute the fields numerically, we divide the aperture into a finite number of grid points and the total field at the  $n^{\text{th}}$  observation point is the cartesian sum of the fields due to all grids on the transmitting aperture.

A computer program based on equation (9) and (10) was developed to compute the transmitting electric field and power flow at an arbitrary distance. The program listing and a sample run is included in Appendix I and II respectively.

### DISCUSSION AND RESULTS

The effects of range and aperture tapering were studied for two identical aperture antennas. The apertures and relevant parameters are described as follows:

Transmitting aperture	$A_1 = 0.7854 \text{ m}^2$ (Dia = 1 m)
Receiving aperture	$A_2 = 0.7854 \text{ m}^2$ (Dia = 1 m)
Operating frequency	$f = 3 \text{ GHz}$
Observation range	$.1 \text{ FF} < R < 1 \text{ FF}$ (FF = $2D^2/\lambda m$ )
Far field range (FF)	FF = 20 m
Taper range	0db, -10dB, -15dB, -20dB, -25dB, -30dB

For the purpose of this report we will consider 50% efficiency to be the minimum in which beam power transmission will be useful. Figure 3 shows the resulting power transfer efficiency as a function of distance when the two apertures are of the same area. This results indicates that beam power is most effective at closer ranges. Uniform aperture illumination was used for the transmitting antenna. Figure 4 and show the results obtained for a cases when the transmitting antenna is two times larger than the receiving aperture. Figure 5 shows the results obtained for cases when the receiving antenna is two times larger than the transmitting antenna. Basically this result shows by increasing the transmitting antenna size does not necessary increase the transmission efficiency. In the contrary increasing the receiving antenna size will increase the amount of power that can be collect. Figure 6 shows the effect of tapering the transmitting aperture on the beam power efficiency at a given distance. Figure 5 indicates a greater efficiency number can be obtained by properly tapering the transmitting aperture. Figure 6 and 7 shows the previous cases

(figure 3 and 4) but with a -20 db taper level introduced in the transmitting aperture. In this case the useful range was increased by 20% .

In general when we consider beam power transmission we have to carefully consider two parameters, the transmitting aperture size and the taper required to efficiently transmit power from point to point. It is also assumed in our discussion that the received antennas will be mechanically steered, therefore scanning will not be an issue. The results presented indicates that beam power should be considered as an alternative for point to point power distribution.

## APPENDIX A

### DESCRIPTION OF PROGRAM

A computer program was designed to calculate the power efficiency between two circular apertures at an arbitrary range. The method of analysis is vector-wave diffraction approach. The main features in this program (BEAM FORTRAN) are the calculation of power transfer efficiency, transmit power density and receive power density. The inputs are modified according to the case inside the program BEAM FORTRAN. The following is a description of all the inputs parameters to the the program BEAM.

#### Input Parameters (BEAM FORTRAN)

LAMBDA	wavelength in mts.
LF	spacing of computation grids
TAREA	transmit area in mts square
RAREA	receive area in mts square
TOTAREA	total area for calculating power radiated in mts square
DZ	fraction of far-field distance ( $2D^2/\lambda$ )
ET	edge taper of transmit aperture fields

#### Example of Inputs and Results

##### INPUTS:

LAMBDA	=	.1
LF	=	.5
TAREA	=	0.7854
RAREA	=	0.7854
TOTAREA	=	1.5708
DZ	=	.1
ET	=	0.

##### RESULTS:

FRACTION OF  $2D^2/\lambda$  = 0.100000024  
DISTANCE BETWEEN APERTURES = 0.157079869E-02 KM  
EDGE TAPER = 0.000000000E+00 DB  
TRANSMITTING APERTURE AREA = 0.785399973 SQ. MTS  
RECEIVING APERTURE AREA = 0.785399973 SQ. MTS  
CAPTURE APERTURE AREA = 1.57079983 SQ. MTS  
TOTAL POWER RADIATED = 0.243498638E-03 W  
TOTAL POWER RECEIVED = 0.221619441E-03 W  
EFFICIENCY PERCENT = 91.0146332 %

## COMPUTER PROGRAM

BEA00010  
BEA00020  
BEA00030  
BEA00040  
BEA00050  
BEA00060  
BEA00070  
BEA00080  
BEA00090  
BEA00100  
BEA00110  
BEA00120  
BEA00130  
BEA00140  
BEA00150  
BEA00160  
BEA00170  
BEA00180  
BEA00190  
BEA00200  
BEA00210  
BEA00220  
BEA00230  
BEA00240  
BEA00250  
BEA00260  
BEA00270  
BEA00280  
BEA00290  
BEA00300  
BEA00310  
BEA00320  
BEA00330  
BEA00340  
BEA00350  
BEA00360  
BEA00370  
BEA00380  
BEA00390  
BEA00400  
BEA00410  
BEA00420  
BEA00430  
BEA00440  
BEA00450  
BEA00460  
BEA00470  
BEA00480  
BEA00490  
BEA00500  
BEA00510  
BEA00520  
BEA00530  
BEA00540  
BEA00550  
BEA00560  
BEA00570  
BEA00580  
BEA00590  
BEA00600

## PROGRAM BEAM

## \*\*\*\*\* PROGRAM DESCRIPTION \*\*\*\*\*

\* THIS PROGRAM CALCULATES THE BEAM POWER EFFICIENCY OF TWO APERTURES  
\* AT AN ARBITRARY RANGE. THE INPUTS ARE THE WAVELENGTH (LAMBDA) IN  
\* METERS, RECEIVING AND TRANSMITTING GRID SPACING AND AREA IN SQ MTS.,  
\* EDGE TAPER IN DBS AND THE SEPARATION BETWEEN THE APERTURES AS A  
\* FRACTION OF  $2D^2/LAMBDA$ .

## \*\*\*\*\* VARIABLES \*\*\*\*\*

\*\*\*\*\* LF - GRID SPACING  
\*\*\*\*\* LAMBDA - WAVELENGTH  
\*\*\*\*\* RAREA - RECEIVING AREA  
\*\*\*\*\* TAREA - TRANSMITTING AREA  
\*\*\*\*\* TOTAREA - CAPTURE AREA  
\*\*\*\*\* DZ - FRACTION OF  $2D^2/LAMBDA$   
\*\*\*\*\* ET - EDGE TAPER  
\*\*\*\*\* K - WAVE NUMBER  
\*\*\*\*\* NO - FREE SPACE IMPEDANCE  
\*\*\*\*\* NXO NXO - NUMBER OF POINTS IN RECEIVING GRID  
\*\*\*\*\* NXL NXL - NUMBER OF POINTS IN TRANSMITTING GRID  
\*\*\*\*\* J -  $\sqrt{-1}$   
\*\*\*\*\* KEM - EQUATION CONSTANT  
\*\*\*\*\* FF - FAR FIELD DISTANCE  
\*\*\*\*\* EFF - EFFICIENCY  
\*\*\*\*\* PERC - EFFICIENCY PERCENT  
\* DXY & DXY - DELTAS FOR RECEIVING GRID  
\* DXY & DXY - DELTAS FOR TRANSMITTING GRID  
\*\*\*\*\* (XO,YO) - POINT IN RECEIVING GRID  
\*\*\*\*\* (XL,YL) - POINT IN TRANSMITTING GRID  
\*\*\*\*\* PR1 - POWER TRANSMITTED  
C\*\*\*\* PR2 - POWER RECEIVED  
\*\*\*\*\* ETX - TRANSMITTED ELECTRIC FIELD  
\* TREX ERX - RECEIVED ELECTRIC FIELD  
\* TRMY HRY - RECEIVED MAGNETIC FIELD

## \*\*\*\*\* VARIABLE DECLARATION \*\*\*\*\*

INTEGER ANO, BNO, CNL, DNL

REAL LAMBDA, LF, M, KEM, K, NO

COMPLEX ERX(300,300), HRY(300,300), ETX(300,300), TREX, TRMY, J

\*\*\*\*\*

## \*\*\*\*\* INPUT DATA \*\*\*\*\*

\*\*\*\*\*

LAMBDA = .1  
LF = .5  
TAREA = 0.7854  
RAREA = 0.7854  
TOTAREA = 1.5708  
DZ = .1  
ET = 0.

## C\*\*\*\* \*\*\* CONSTANTS \*\*\*

J = (0.,1.)  
PI = 4 \* ATAN(1.)  
NO = 120 \* PI  
XAL =  $\sqrt{TAREA} / 2$   
XAO =  $\sqrt{RAREA} / 2$   
XAT =  $\sqrt{TOTAREA} / 2$   
K =  $2. * PI / LAMBDA$   
KEM =  $1. / (4. * PI)$   
DXY =  $LAMBDA * LF$   
NXL =  $2. * XAL / DXY + 1.1$   
NXO =  $2. * XAO / DXY + 1.1$

NXT	= 2. * XAT / DXY + 1.1	BEA00610
M	= 10**(-ET / 20)	BEA00620
FF	= (2. * (2. * XAL)**2. / LAMBDA) * DZ	BEA00630
C****		BEA00640
C****		BEA00650
C****		BEA00660
C****	*** LOOP FOR TRANSMITTING GRIDS ***	BEA00670
	DO 50 CNL = 1, NXL	BEA00680
	XL = -XAL + DXY * (CNL - 1)	BEA00690
	DO 25 DNL = 1, NXL	BEA00700
	YL = -XAL + DXY * (DNL - 1)	BEA00710
C****	*** TRANSMITTED ELECTRIC FIELD ***	BEA00720
	ETX(CNL,DNL) = M + (1. - M) * (1. - (XL**2 + YL**2) / (XAL**2))**2	BEA00730
1		BEA00740
25	CONTINUE	BEA00750
50	CONTINUE	BEA00760
C****		BEA00770
C****		BEA00780
C****		BEA00790
C****	*** LOOP FOR RECEIVING GRIDS ***	BEA00800
C****		BEA00810
C****		BEA00820
C****		BEA00830
C****		BEA00840
	DO 200 ANO = 1, NXT	BEA00850
	XO = -XAT + DXY * (ANO - 1)	BEA00860
	DO 100 BNO = 1, NXT	BEA00870
	YO = -XAT + DXY * (BNO - 1)	BEA00880
C****		BEA00890
C****		BEA00900
C****	***** SUBROUTINE FOR RECEIVED FIELDS CALCULATION *****	BEA00910
C****		BEA00920
C****		BEA00930
C****		BEA00940
1	CALL EANDH(M,K,J,NXL,XAL,DXY,FF,NO,KEM, TREX,TRMY,ETX,XO,YO)	BEA00950
	ERX(ANO,BNO) = TREX	BEA00960
	HRY(ANO,BNO) = TRMY	BEA00970
	TREX = 0	BEA00980
	TRMY = 0	BEA00990
100	CONTINUE	BEA01000
200	CONTINUE	BEA01010
C****		BEA01020
C****		BEA01030
C****		BEA01040
C****	***** SUBROUTINE FOR POWER AND EFFICIENCY CALCULATION *****	BEA01050
C****		BEA01060
C****		BEA01070
C****		BEA01080
C****		BEA01090
1	CALL FINISH(ERX,HRY,M,NXL,NXO,ET,ETX,KEM,LF,RAREA,TAREA, TOTAREA,XAL,XAO,DXY,DZ,XO,YO,NO,FF,NXT,XAT)	BEA01100
	STOP	BEA01110
	END	BEA01120
C****		BEA01130
C****	*****	BEA01140
C****		BEA01150
C****		BEA01160
C****	THIS SUBROUTINE CALCULATES THE XYZ COMPONENTS OF THE RECEIVED	BEA01170
C****	ELECTRIC AND MAGNETIC FIELDS FOR EVERY POINT IN THE RECEIVING	BEA01180
C****	APERTURE BY ADDING THE EFFECT OF EVERY POINT IN THE TRANSMITTING	BEA01190
C****	APERTURE.	BEA01200

C****		BEA01210
C****	*****	BEA01220
	SUBROUTINE EANDH(M,K,J,NXL,XAL,DXY,FF,NO,KEM,TREX,TRMY,ETX,XO,YO)	BEA01230
	REAL M,KEM,K,NO	BEA01240
	INTEGER CNL,DNL	BEA01250
	COMPLEX J,PHASOR,EFOX,ESOX,ETX(300,300),REX,RMY,TREX,TRMY	BEA01260
C****	*** LOOP FOR TRANSMITTING GRIDS ***	BEA01270
	DO 200 CNL = 1, NXL	BEA01280
	XL = -XAL + DX Y * (CNL-1)	BEA01290
	DO 100 DNL = 1, NXL	BEA01300
	YL = -XAL + DX Y * (DNL - 1)	BEA01310
C****		BEA01320
C****		BEA01330
C****	*** DISTANCE ***	BEA01340
C****		BEA01350
C****		BEA01360
	R = SQRT((XO-XL)**2 + (YO-YL)**2 + FF**2)	BEA01370
C****		BEA01380
C****	*** COS X ***	BEA01390
C****		BEA01400
C****		BEA01410
	COSX = FF / R	BEA01420
C****		BEA01430
C****		BEA01440
C****		BEA01450
C****		BEA01460
C****	*** FIRST ORDER RECEIVED ELECTRIC FIELD ***	BEA01470
C****		BEA01480
C****		BEA01490
C****		BEA01500
	PHASOR = (COS(K*R) - J*SIN(K*R)) / R	BEA01510
	EFOX = J * K * ETX(CNL,DNL) * COSX * PHASOR	BEA01520
C****		BEA01530
C****		BEA01540
C****	*** SECOND ORDER RECEIVED ELECTRIC FIELD ***	BEA01550
C****		BEA01560
C****		BEA01570
	PHASOR = (COS(K*R) - J*SIN(K*R)) / R**2	BEA01580
	ESOX = ETX(CNL,DNL) * COSX * PHASOR	BEA01590
C****		BEA01600
C****		BEA01610
C****		BEA01620
C****	*** COMBINED RECEIVED ELECTRIC ELECTRIC FIELDS ***	BEA01630
C****		BEA01640
C****		BEA01650
C****		BEA01660
	REX = KEM * (EFOX + ESOX) * DX Y * DX Y	BEA01670
C****	*** RECEIVED MAGNETIC FIELD ***	BEA01680
	RMY = REX / NO	BEA01690
C****		BEA01700
C****		BEA01710
C****	*** TOTAL FIELDS ***	BEA01720
C****		BEA01730
C****		BEA01740
C****		BEA01750
	TREX = TREX + REX	BEA01760
	TRMY = TRMY + RMY	BEA01770
100	CONTINUE	BEA01780
200	CONTINUE	BEA01790
		BEA01800

RETURN	BEA01810
END	BEA01820
C**** *****	BEA01830
C****	BEA01840
C**** THIS SUBROUTINE CALCULATES THE TOTAL POWER RECEIVED, TOTAL	BEA01850
C****	BEA01860
C**** POWER TRANSMITTED AND EFFICIENCY PERCENT.	BEA01870
C****	BEA01880
C**** *****	BEA01890
C****	BEA01900
C****	BEA01910
C****	BEA01920
SUBROUTINE FINISH(ERX,HRY,M,NXL,NXO,ET,ETX,KEM,LF,RAREA,TAREA,	BEA01930
1                    TOTAREA,XAL,XAO,DXY,DZ,XO,YO,NO,FF,NXT,XAT)	BEA01940
REAL LF,M,KEM,NO	BEA01950
INTEGER ANO,BNO	BEA01960
COMPLEX ERX(300,300),HRY(300,300),ETX(300,300)	BEA01970
C****	BEA01980
C**** ***** TOTAL POWER RADIATED *****	BEA01990
C****	BEA02000
C****	BEA02010
PR1 = 0	BEA02020
DSZO = DXY * DXY	BEA02030
DO 200 ANO = 1, NXT	BEA02040
DO 100 BNO = 1, NXT	BEA02050
DSZO = DXY * DXY	BEA02060
PR1 = .5 * REAL(ERX(ANO,BNO) * CONJG(HRY(ANO,BNO)))	BEA02070
1                * DSZO + PR1	BEA02080
100        CONTINUE	BEA02090
200        CONTINUE	BEA02100
C****	BEA02110
C****	BEA02120
C****	BEA02130
C**** ***** TOTAL POWER RECEIVED *****	BEA02140
C****	BEA02150
PR2 = 0	BEA02160
N1 = (-XAO + XAT) / DXY + 1.1	BEA02170
N2 = (XAO + XAT) / DXY + 1.1	BEA02180
DO 800 ANO = N1, N2	BEA02190
DO 900 BNO = N1, N2	BEA02200
PR2 = .5 * REAL(ERX(ANO,BNO) * CONJG(HRY(ANO,BNO)))	BEA02210
1                * DSZO + PR2	BEA02220
900        CONTINUE	BEA02230
800        CONTINUE	BEA02240
C**** ***** EFFICIENCY PERCENT CALCULATION *****	BEA02250
C****	BEA02260
EFF = PR2 / PR1	BEA02270
PERC = EFF * 100	BEA02280
C****	BEA02290
C**** *** OUTPUT DATA ***	BEA02300
WRITE(9,*) 'FRACTION OF 2*D**2/LAMBDA = ',DZ	BEA02310
WRITE(9,*) 'DISTANCE BETWEEN APERTURES = ',FF/1000,'KM'	BEA02320
WRITE(9,*) 'EDGE TAPER = ',ET,'DB'	BEA02330
WRITE(9,*) 'TRANSMITTING APERTURE AREA = ',TAREA,'SQ. MTS'	BEA02340
WRITE(9,*) 'RECEIVING APERTURE AREA = ',RAREA,'SQ. MTS'	BEA02350
WRITE(9,*) 'CAPTURE APERTURE AREA = ',TOTAREA,'SQ. MTS'	BEA02360
WRITE(9,*) 'TOTAL POWER RADIATED = ',PR1,'W'	BEA02370
WRITE(9,*) 'TOTAL POWER RECEIVED = ',PR2,'W'	BEA02380
WRITE(9,*) 'EFFICIENCY PERCENT = ',PERC,'%'	BEA02390
RETURN	BEA02400

END

BEA02410

```
/*EXEC TO RUN BPE*/  
SETUP FTN  
"FTNLIB"  
"FI 09 DISK CAACOSTA BPE a1"  
"LOAD beam (start"
```

## REFERENCES

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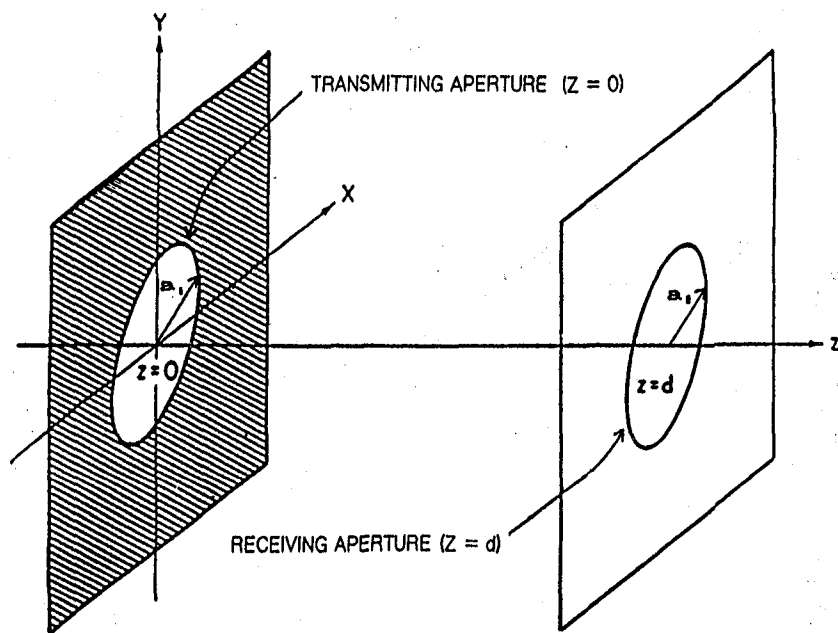


Figure 1. Geometry for calculating the transmission efficiency

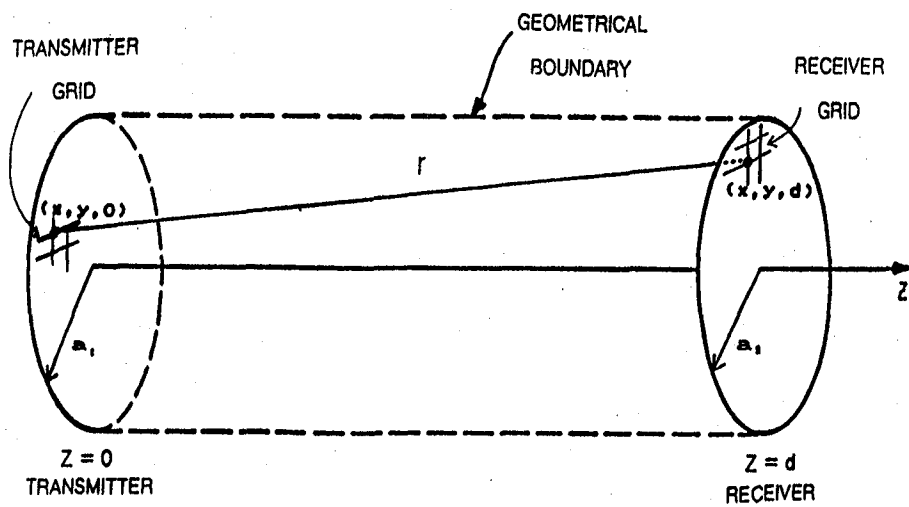


Figure 2. Parameters description for obtaining beam power efficiency

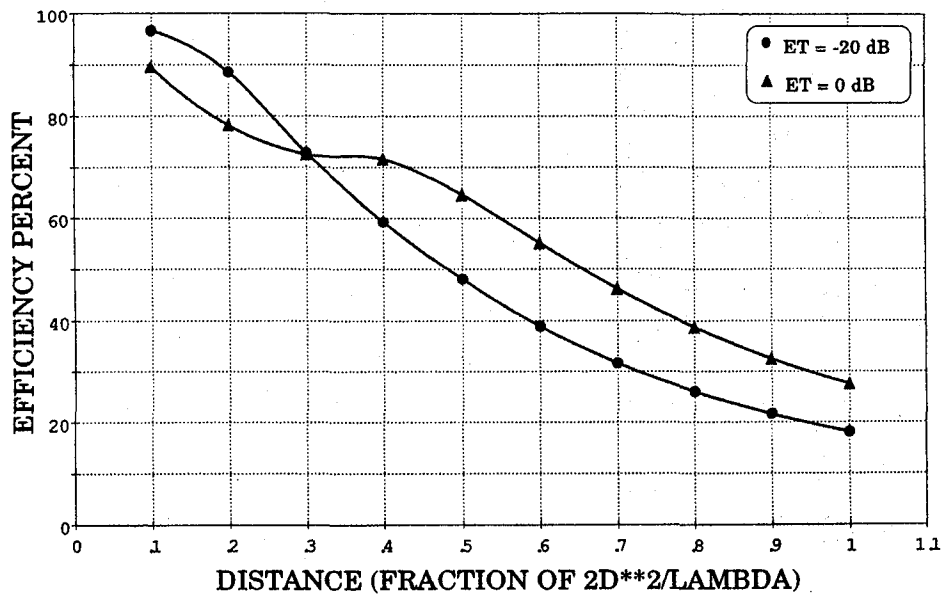


Figure 3. Efficiency curves resulting from equal areas with two different tapers

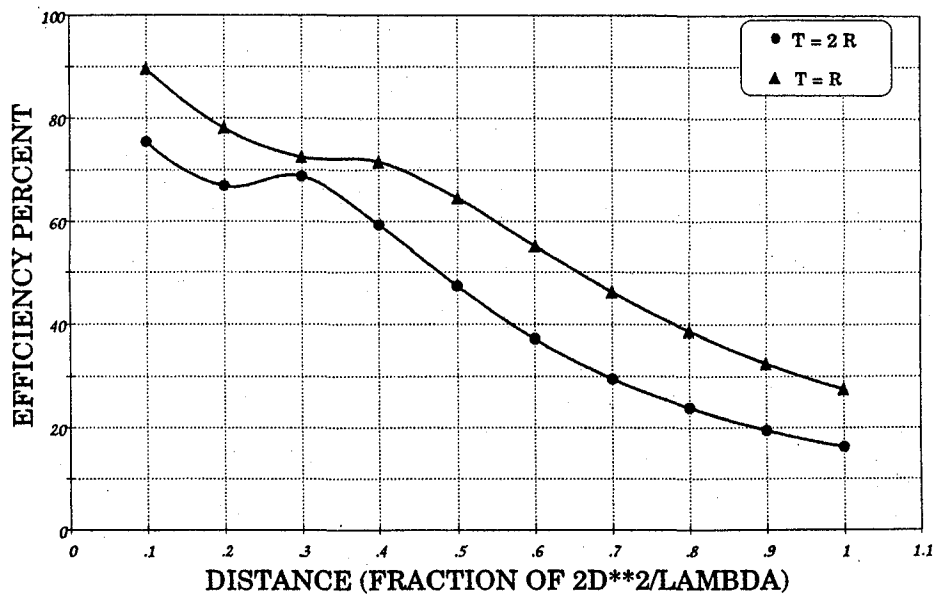


Figure 4. Efficiency curves resulting from different transmitting and receiving apertures size .

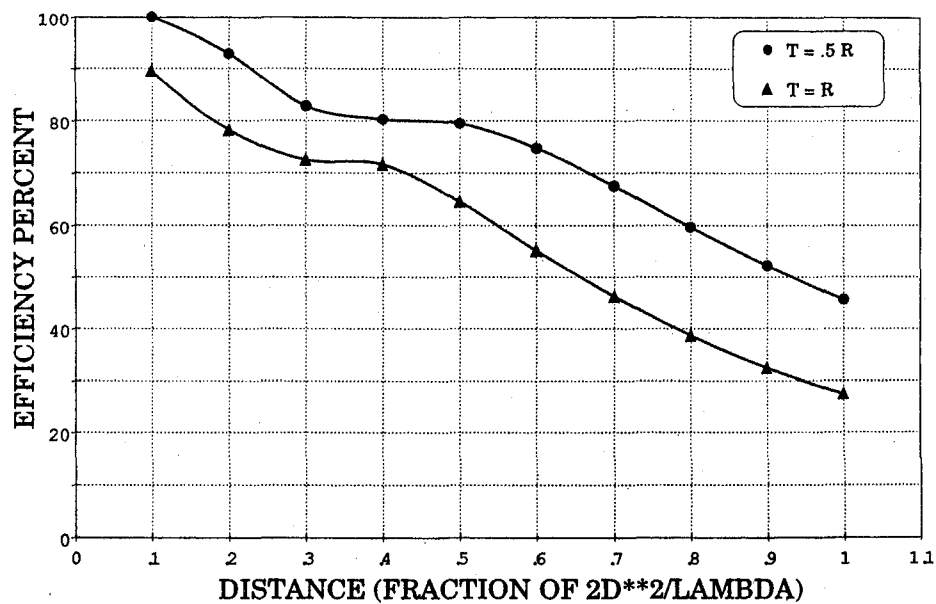


Figure 5. Efficiency curves resulting from different transmitting and receiving apertures size .

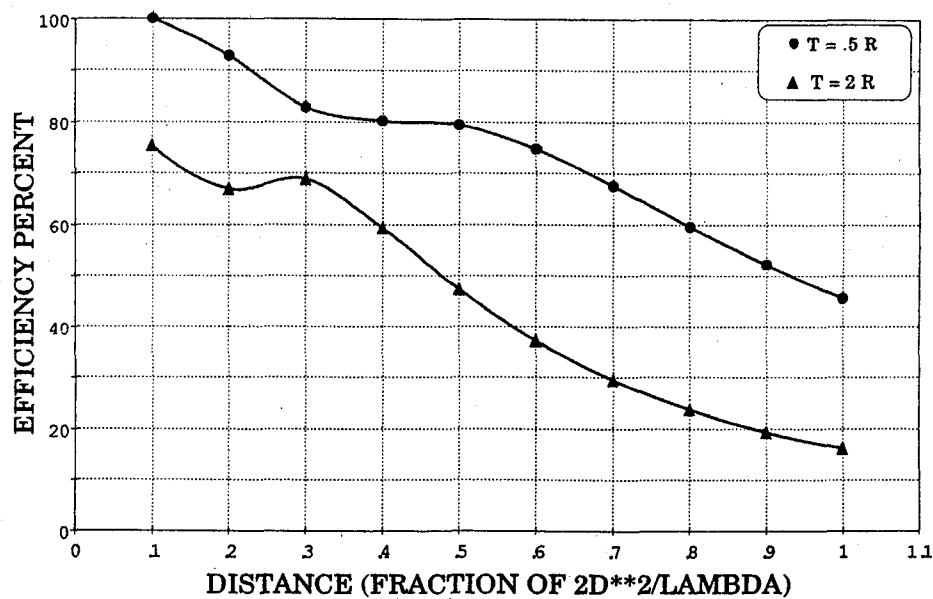


Figure 6. Efficiency curves resulting from different transmitting and receiving apertures size .

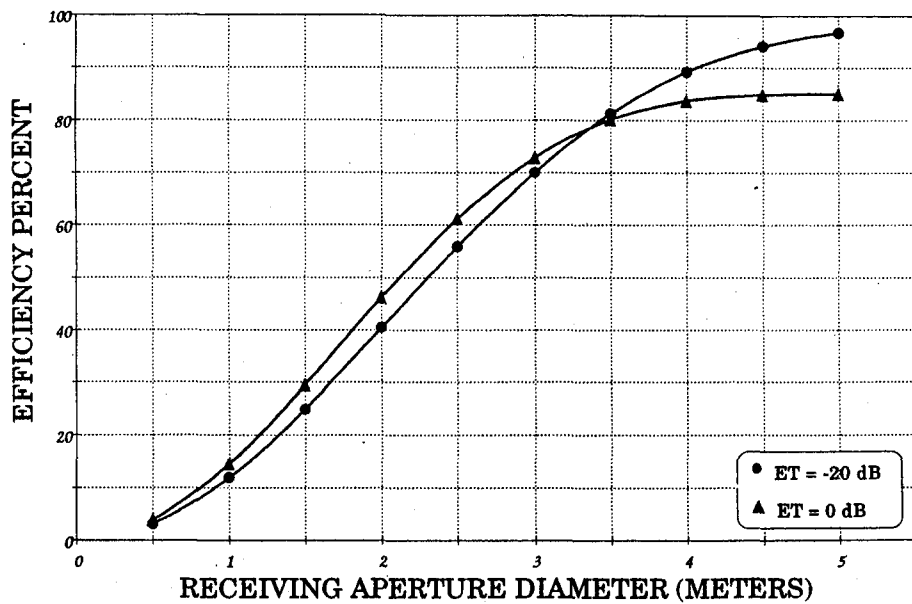


Figure 7. Efficiency curves for different receiving aperture size at far-field range

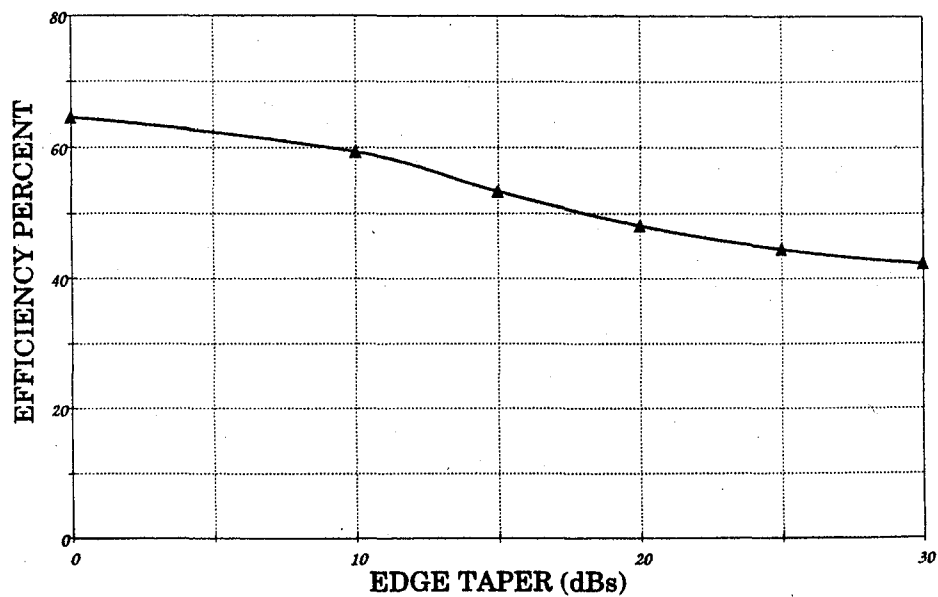


Figure 8. Efficiency curve for different transmitting aperture tapers at near-field range.

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